

Evaluating Red Mud as a High-Performance Substitute for Calcite in Drilling Reservoir Sections

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ABSTRACT

Red mud, an aluminum production waste, presents a significant industrial waste challenge worldwide. In recent studies, red mud utilization in construction materials and environmental remediation has been explored; however, its applications for improving drilling fluid performance in the oil industry require further investigation. In this study, the feasibility of using red mud as an alternative to calcite in water-based drilling fluids was investigated. Five drilling fluid formulations with varying calcite-to-red mud ratios were evaluated by comprehensive laboratory testing. The optimal performance parameters were determined in terms of rheological properties, gel strength characteristics, and corrosion resistance. Red mud was found to effectively substitute calcite, while maintaining acceptable drilling fluid properties. The pure red mud formulation (sample S2) exhibited a competitive apparent viscosity (25.0 cP) and superior plastic viscosity (23.0 cP) compared to pure calcite (27.5 and 11.0 cP, respectively). Mixed formulations (S3, S4, and S5) afforded optimal cutting transport efficiency with the ratios of yield point to plastic viscosity in the range of 1.00–1.08. To conclude, the results of this study confirmed the potential of red mud as a sustainable and cost-effective alternative that addresses environmental waste disposal challenges, while satisfying the requirements of drilling operation.

Keywords: red mud, drilling fluid, calcite replacement, waste utilization, aluminum waste, sustainable drilling

1. INTRODUCTION

The oil and gas industry is continuously seeking sustainable alternatives to conventional drilling fluid components owing to increasing environmental regulations and cost optimization requirements^{1,2}. Drilling fluids perform multiple critical functions, including maintenance of wellbore stability, control of formation pressure, transport of drill cutting, and cooling of equipment. Traditional formulations rely heavily on processed materials like calcite, which, although effective, contribute to operational costs and resource depletion^{3,4}.

Red mud presents one of the most significant industrial waste disposal challenges worldwide. Approximately 150 million tons of this highly alkaline byproduct of the Bayer process is generated annually worldwide, with each ton of aluminum production creating 2–3 tons of red mud waste. The high pH (10–13) and complex mineralogy of the material, including iron oxides (30–60%), aluminum oxides (10–20%), and silicates (3–50%), have historically limited options for disposal in containment ponds and landfills, creating long-term environmental liabilities^{5–8}.

Recently, extensive research has identified the potential applications for red mud in construction materials^{9,10} and environmental remediation^{11,12}. However, there have been only a few studies on the application of red mud in the oil industry, including drilling fluids¹³ and cementing^{14–17}. The fine particle size,

alkaline nature, and mineral composition of the material suggest its compatibility with drilling fluid requirements.

The chemical composition of red mud depends on the source and processing conditions of the bauxite ore. The major constituents include iron oxides, which provide the characteristic red coloration, aluminum oxides from incomplete extraction, and silicates from the original ore impurities. Recent studies have demonstrated that the pozzolanic properties of red mud make it suitable for application in cement and other construction materials^{18–20}.

Effective drilling fluids must maintain specific rheological profiles to ensure proper cutting transport, while minimizing formation damage. The key parameters include the plastic viscosity for mechanical friction resistance, yield point for cutting suspension, and gel strength for static settling prevention. The optimal ratio of yield point to plastic viscosity ranges from 0.5 to 1.5 for efficient hydraulic performance^{21–24}.

Various waste materials have been explored in previous studies for drilling fluid applications, including agricultural rice waste^{25,26} and industrial byproducts^{13,27}. These studies have shown the feasibility of waste integration, while maintaining or improving drilling fluid performance, thereby supporting the theoretical foundation for red mud utilization.

In this study, the effect of replacing calcite, which is commonly used as a weighting material while drilling through a reservoir



Figure 1. Red mud waste material collected from the Ma'aden plant

section, by red mud was evaluated. The evaluation included testing the effect of partial and full replacement of calcite with red mud and evaluating the effect of this replacement on the drilling fluid properties, particularly its rheology and corrosion effect.

2. MATERIALS AND METHODOLOGY

2.1. Materials. Industrial waste was obtained from an aluminum production facility (Ma'aden plant), characterized by a pH of 12.5 and specific gravity of 2.85. To evaluate the effect of the particle size distribution, the material was classified into three distinct grades: fine (75–125 μm), medium (212–250 μm), and large (250–425 μm). The material exhibits the characteristic reddish-brown coloration due to high iron oxide content, as shown in the collected sample (Figure 1). The calcite used in this study was a commercial grade drilling fluid additive (>95% CaCO_3) with a particle size distribution (PSD) of 75–125 μm (fine calcite); other chemical additives included a defoamer, XC polymer, modified starch, and potassium chloride.

2.2. Experimental Program. Five distinct formulations were prepared in this study; which had the same content of defoamer, XC polymer, starch, and KCl, and differed in calcite and red mud content. The first sample (control sample, S1) was prepared to contain 100% calcite; the second sample S2 contained 100% red mud; and the other three samples (S3, S4, and S5) were prepared by replacing 75%, 50%, and 25% of calcite with red mud, respectively. Table 1 lists the compositions of the five samples.

The systematic variation in the calcite-to-red mud ratios allowed for a comprehensive evaluation of the performance characteristics across the entire substitution spectrum. Visual differences in the prepared samples were evident, with color intensity correlating directly with the red mud content concentration. Figure 2 shows drilling fluid samples S3–S5, showing visual differences in color and consistency based on the calcite-to-red mud ratios before corrosion testing.

The red mud used in this study had a specific gravity of 2.80. It was collected from the Ma'aden plant for aluminum manufacturing, located in Ras Al Khair in the Eastern province of Saudi Arabia, which is more than 2 km in length and 1 km in width, as shown in Figure 3.

After collecting the red mud sample, it was dried at 105 °C for 2 h to remove the moisture content and grinded to an average particle size smaller than 100 microns. The samples were then characterized using X-ray fluorescence (XRF) and scanning electron microscopy (SEM) analysis. The elemental composition of red mud listed in Table 2 shows that red mud is dominated by iron and aluminum oxides at 26.5% and 23.5%, with a high silicon oxide content of 15.2%.

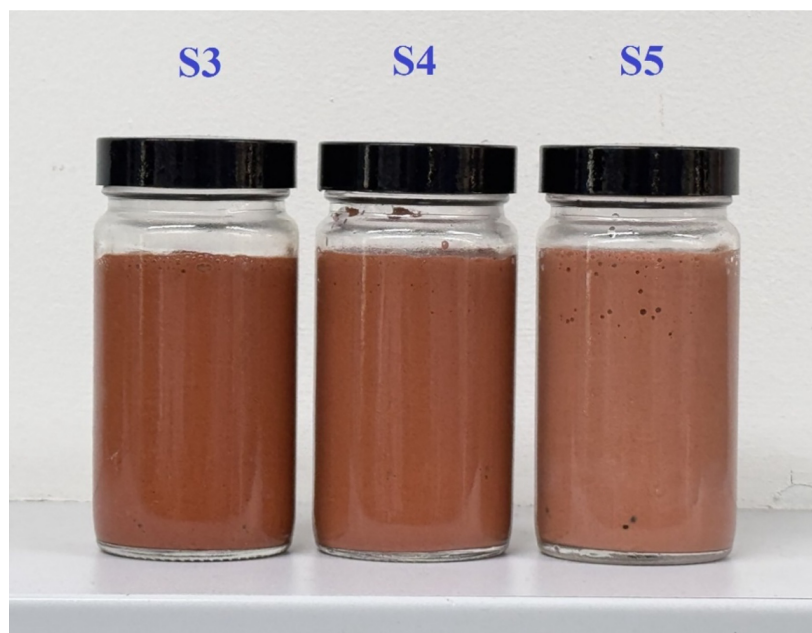
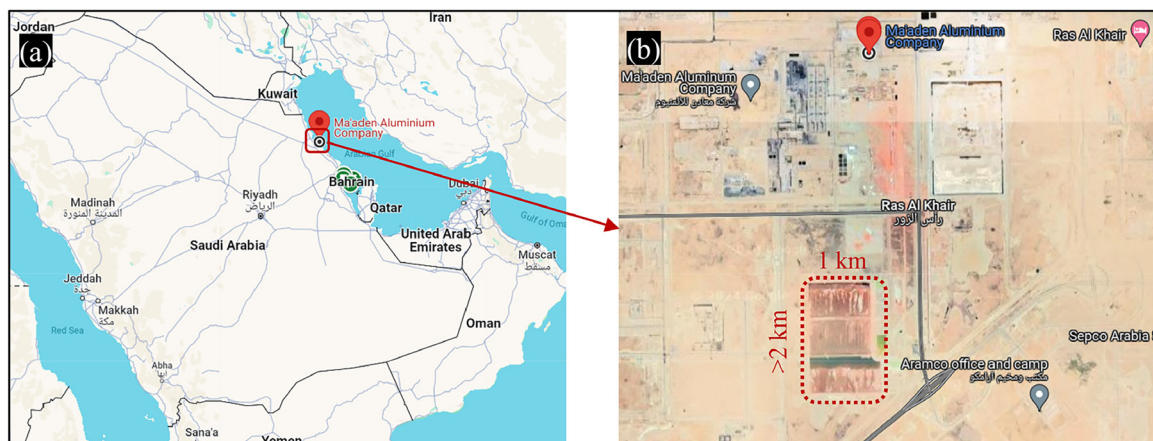
The red mud sample was also characterized using SEM. As shown in the SEM image in Figure 4, the red mud powder is dominated by small size particles of less than 5 μm .

2.2.1. Methodology. After drilling fluid preparation according to the composition listed in Table 1, the pH of the slurries was measured directly after preparation. Accurate pH measurement serves as a critical quality control parameter, particularly in red mud-based formulations, because of their highly alkaline nature. This process requires precise calibration and standardized techniques to ensure reliable results. After pH measurement, the slurry density was also measured for all samples using a mud balance.

2.3. Rheological Analysis. Four rheological properties were measured in this study: plastic viscosity, apparent viscosity, yield point, and 10-s and 10-min gel strengths. Rheological measurements were performed using a rotational viscometer at standard speeds (600, 300, 200, 100, 6, and 3 RPM) following API RP 13B-1 protocols. Testing was conducted at ambient pressure and a temperature of 150 °F. From the rheology testing, the dial readings at different RPM values, as listed in Table 3 were recorded and used to calculate the rheological properties using

Table 1. Comprehensive sample formulation matrix

Component	S1 (Control)	S2 (Full RM)	S3 (High RM)	S4 (Equal Mix)	S5 (Low RM)	Units
Water	350.0	350.0	350.0	350.0	350.0	gm
Defoamer	0.10	0.10	0.10	0.10	0.10	gm
XC Polymer	1.50	1.50	1.50	1.50	1.50	gm
Starch	6.0	6.0	6.0	6.0	6.0	gm
KCl	60.0	60.0	60.0	60.0	60.0	gm
Fine Calcite	80 (100%)	0	20 (25%)	40 (50%)	60 (75%)	gm
Red Mud	0	80 (100%)	60 (75%)	40 (50%)	20 (25%)	gm

**Figure 2.** Color variations of samples S3, S4, and S5 due to different red mud contents**Figure 3.** (a) Location of the Ma'aden Aluminum Company in the Eastern province of Saudi Arabia and (b) Ma'aden red mud pools with a size of more than 2 km in length and 1 km in width¹⁷

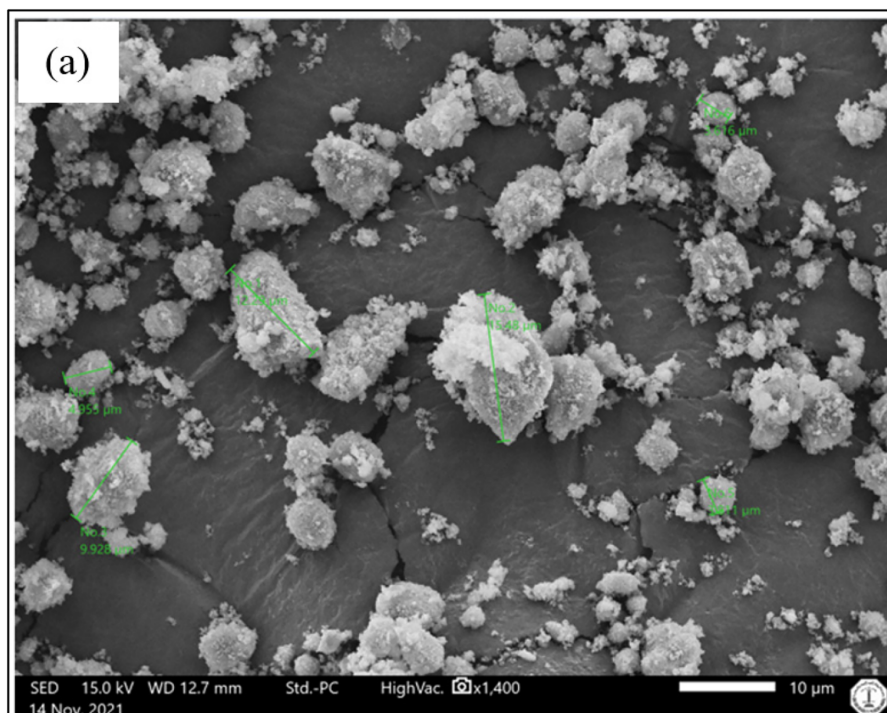


Figure 4. SEM image of the red mud sample

Eqs. (1)–(4).

$$AV (cP) = \theta_{600} / 2 \quad (1)$$

$$PV (cP) = \theta_{600} - \theta_{300} \quad (2)$$

$$YP (lb_f/100 ft^2) = \theta_{300} - PV \quad (3)$$

$$\text{Cutting transport efficiency indicator} = YP/PV \quad (4)$$

Table 2. Elemental composition of the red mud sample characterized by XRF

Element	Concentration (%)
Al ₂ O ₃	23.5
Fe ₂ O ₃	26.5
SiO ₂	15.1
TiO ₂	7.40
ZrO ₂	0.28
P ₂ O ₅	0.38
Cr ₂ O ₃	0.11
CaO	6.35
MgO	0.17
MnO	0.03
ZnO	0.01
K ₂ O	0.04
Na ₂ O	9.40
SO ₃	0.96
V ₂ O ₅	0.07
Loss on Ignition	9.70

Where AV is the apparent viscosity; PV is the plastic viscosity; YP is the yield point; and θ_{600} and θ_{300} represent the dial readings of the viscometer at 600 and 300 rpm, respectively, as listed in Table 3.

2.4. Corrosion Rate Testing. Standardized metal coupons were exposed to each of the five drilling fluid formulations being studied for 6 h under a controlled high-pressure of 1000 psi and a temperature of 100 °C. The testing apparatus ensured consistent environmental conditions throughout the exposure period using gravimetric analysis to determine the corrosion rates.

3. RESULTS AND DISCUSSION

3.1. Drilling Fluid Density and pH Variation. The density and pH of the drilling fluids were measured directly after the slurry preparation. Figure 5 compares the pH values of the five drilling fluid formulations, whereas Figure 6 presents the corresponding density values. The results for these properties are compared in Table 4. The results show that there was no significant change in the density and pH of the drilling fluid sample after

Table 3. Raw viscometer readings

RPM	S1	S2	S3	S4	S5
600	55	50	36	36	39
300	44	27	24	24	26.5
200	40	22	19	19	21
100	34	15	13	13	14
6	25	5	4	4	5
3	25	4.5	3	3.5	4

Table 4. Physical property comparison

Sample	Composition	pH	Density (ppg)	Alkalinity	Environmental Impact
S1	100% Calcite	10.7	10.2	Moderate	Standard
S2	100% Red Mud	11.2	10.9	High	Beneficial waste use
S3	25% Calcite + 75% Red Mud	11.1	10.7	High	Significant waste use
S4	50% Calcite + 50% Red Mud	11.0	10.5	Moderate-High	Moderate waste use
S5	75% Calcite + 25% Red Mud	10.8	10.1	Moderate	Limited waste use

Table 5. Comprehensive rheological properties for all samples

Sample	Composition	Apparent Viscosity (cP)	Plastic Viscosity (cP)	Yield Point (lb/100 ft ²)	Yield Point/Plastic Viscosity Ratio	Classification
S1	100% Calcite	27.5	11	33.0	3.00	High Yield Point
S2	100% Red Mud	25.0	23	4.0	0.17	High Plastic Viscosity
S3	25% Calcite + 75% Red Mud	18.0	12	12.0	1.00	Balanced
S4	50% Calcite + 50% Red Mud	18.0	12	12.0	1.00	Balanced
S5	75% Calcite + 25% Red Mud	19.5	13	14.0	1.08	Balanced

replacing calcite with red mud. The sample containing 100% calcite exhibited a density and pH of 10.2 ppg and 10.7, respectively. The sample with 100% red mud exhibited a density and pH of 10.9 ppg and 11.2, respectively, where the density decreased by 6.9% and the pH was increased by 4.7% compared to those of the control sample S1.

3.2. Rheological Parameters. The calculated rheological parameters revealed significant performance variations across the formulations, providing insights into the optimal mixing ratios for field applications. Table 5 presents a summary of the apparent viscosity, plastic viscosity, yield point, and yield point/plastic viscosity ratio for all samples. Rheological analysis demonstrated clear performance distinctions between pure calcite and red mud formulations, with mixed systems providing an optimal balance for drilling operations.

The apparent viscosity analysis demonstrated the competitive performance of red mud relative to that of calcite. Sample S2 (pure red mud) achieved 25.0 cP, representing only a 9%

reduction from Sample S1 (pure calcite) at 27.5 cP. This minimal difference suggests that the red mud maintains adequate flow resistance for drilling applications. Mixed formulations (S3–S5) exhibited lower apparent viscosities (18.0–19.5 cP), indicating potential advantages for applications requiring enhanced flow characteristics. This trend suggests that partial red mud substitution may optimize the pumping requirements while maintaining functional performance. This observation is consistent with the findings of Leal et al.²⁸, who reported that environmentally friendly drilling fluid formulations can maintain proper rheological performance while improving drilling fluid behavior.

As shown in Figure 7, a remarkable finding emerged from the plastic viscosity comparison, where Sample S2 demonstrated superior performance (23.0 cP) to Sample S1 (11.0 cP). This 109% improvement indicates the exceptional ability of the red mud to resist mechanical friction, potentially reducing wear on drilling equipment and improving hole cleaning efficiency.

The enhanced plastic viscosity likely resulted from the fine particle size distribution and surface characteristics of the red

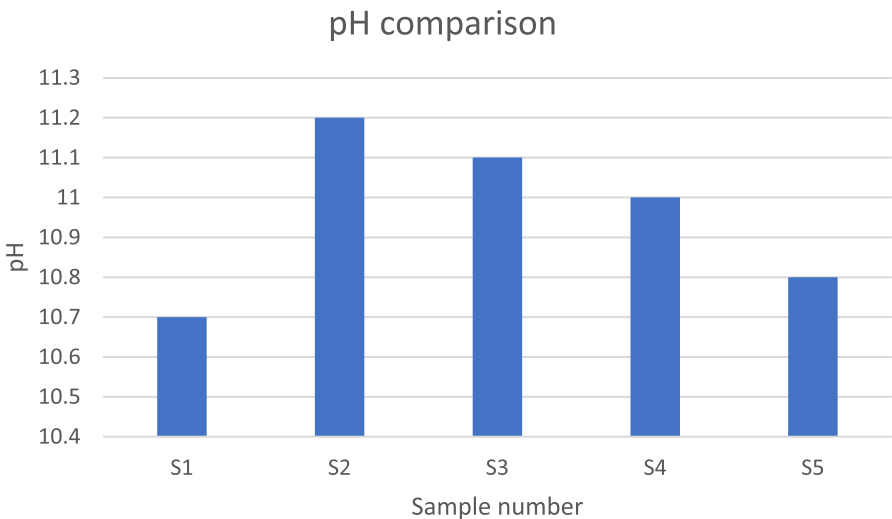


Figure 5. pH comparison

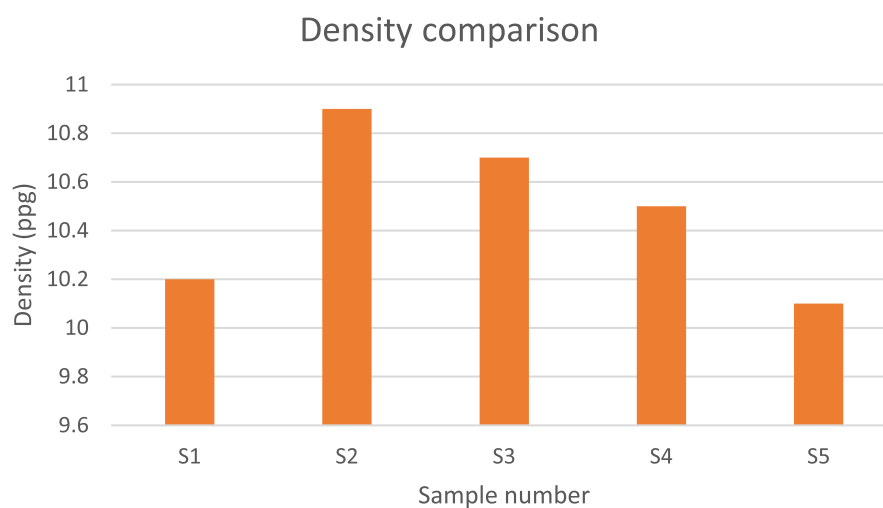


Figure 6. Density comparison

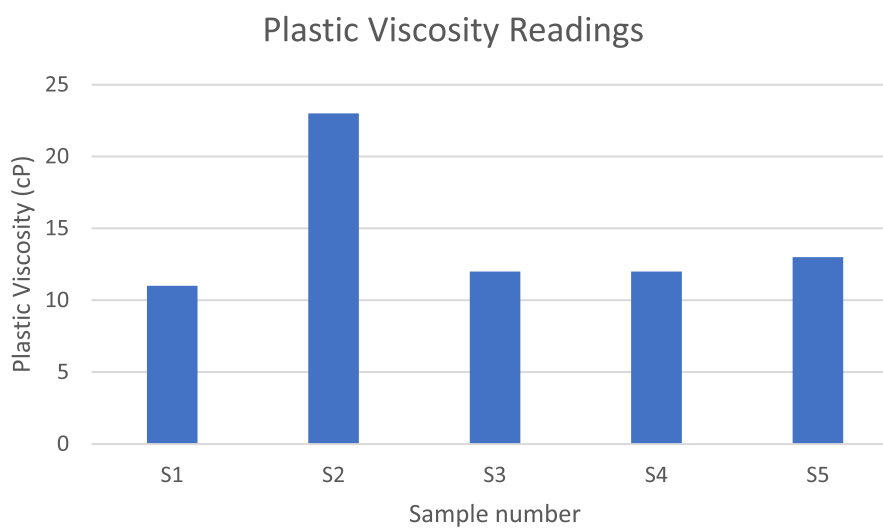


Figure 7. Plastic Viscosity Readings

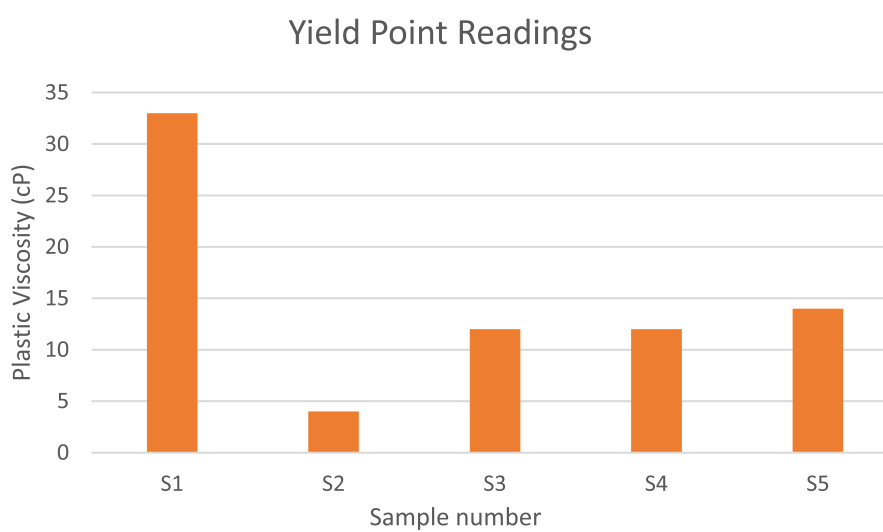


Figure 8. Yield Point Readings

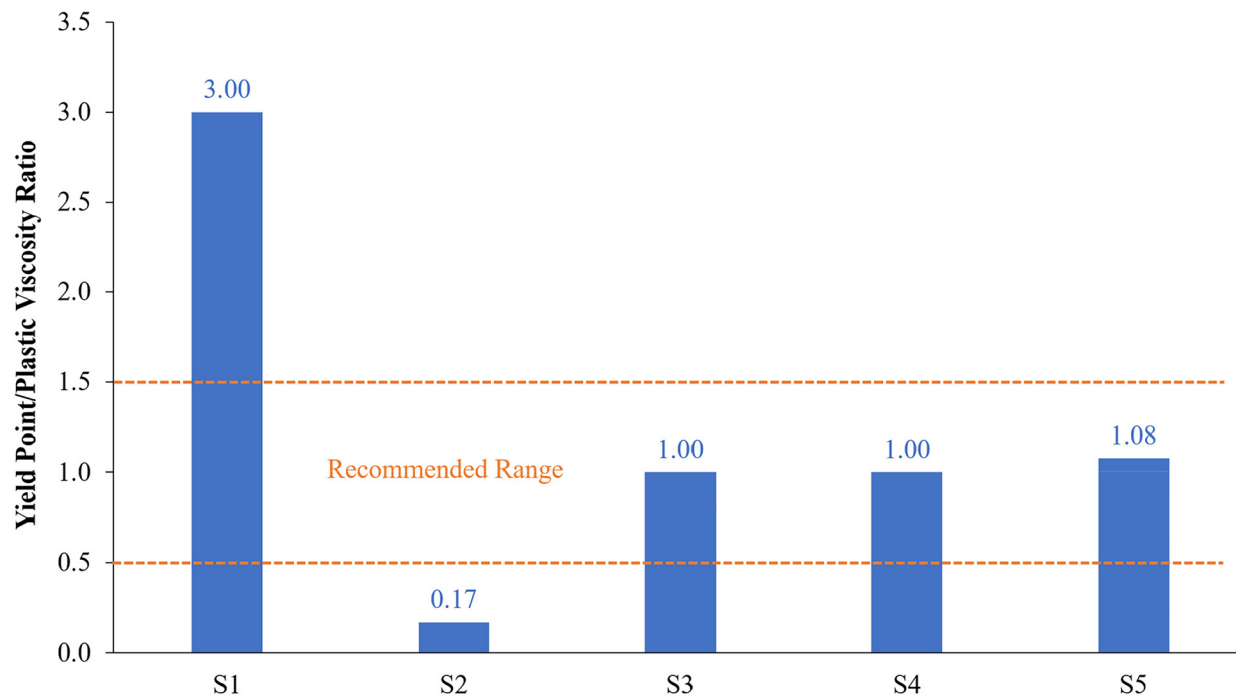


Figure 9. Yield point/plastic viscosity ratios of all samples

mud, creating increased internal friction within the fluid matrix. Similar behavior has been reported in previous studies, where fine mineral additives improved the plastic viscosity of water-based drilling fluids due to their high particle interaction in the drilling fluid²⁸. This property is particularly valuable in challenging drilling environments, where equipment protection and cutting transport efficiency are paramount. As reported by Al-Yasiri et al., red mud improved the rheological performance of water-based drilling fluids while maintaining good suspension and filtration properties²⁹.

As shown in Table 5 and Figure 8, the yield point analysis revealed critical differences in the cutting transport capability. Sample S1 (calcite) exhibited an excessive yield point (33.0 lb/100 ft²), resulting in a 3.00 yield point/plastic viscosity ratio, as shown in Figure 9, which is well above the recommended range of 0.5–1.5. This high ratio indicates potential difficulties in pump circulation and energy loss during operation.

Conversely, sample S2 (red mud) exhibited an extremely low yield point (4.0 lb/100 ft²) with a yield point/plastic viscosity ratio of 0.17, as shown in Figure 9, suggesting an inadequate cutting suspension capability. Although energy-efficient, this formulation may not provide sufficient lifting force for effective hole cleaning.

The mixed formulations (S3–S5) achieved an optimal balance with yield point/plastic viscosity ratios of 1.00–1.08, as shown in Figure 9, falling within the industry-recommended parameters. These results strongly support blended approaches over pure-component systems for practical drilling applications. This agrees with previous studies showing that balanced rheological properties are essential for improving drilling fluid performance and cuttings transportation²⁸.

The gel strength results demonstrated acceptable performance across all formulations, with values in the range of 2–4 lb/100

ft², as shown in Table 6 and Figure 10. Sample S3 exhibited ideal behavior with stable gel development, indicating that balanced thixotropic properties are essential for drilling operations. The consistency between the readings taken at 10 s and 10 min suggests reliable suspension characteristics during temporary circulation stoppages.

3.3. Corrosion Resistance Evaluation. The corrosion testing program maintained consistent pressure conditions throughout the 6 h exposure period, ensuring reliable and reproducible results across all sample formulations. Corrosion resistance results demonstrated acceptable performance across all formulations, with weight losses well below 0.5%. Sample S5 achieved outstanding performance (0.01%), whereas sample S2 showed higher but still acceptable corrosion rates (0.34%). These results support the compatibility of red mud with standard drilling equipment and validate its potential for field applications.

3.4. Study Limitations. This study was carried out under laboratory conditions using five drilling fluid formulations. Although the results showed that red mud can be used as a substitute for calcite, the evaluation was limited to density, pH, rheological properties, gel strength, and short-term corrosion resistance. Other important properties, such as filtration performance,

Table 6. Gel strength analysis

Sample	10 s Gel Strength (lb/100 ft ²)	10 min Gel Strength (lb/100 ft ²)
S1	2	3
S2	3	4
S3	3	3
S4	3	4
S5	2	4

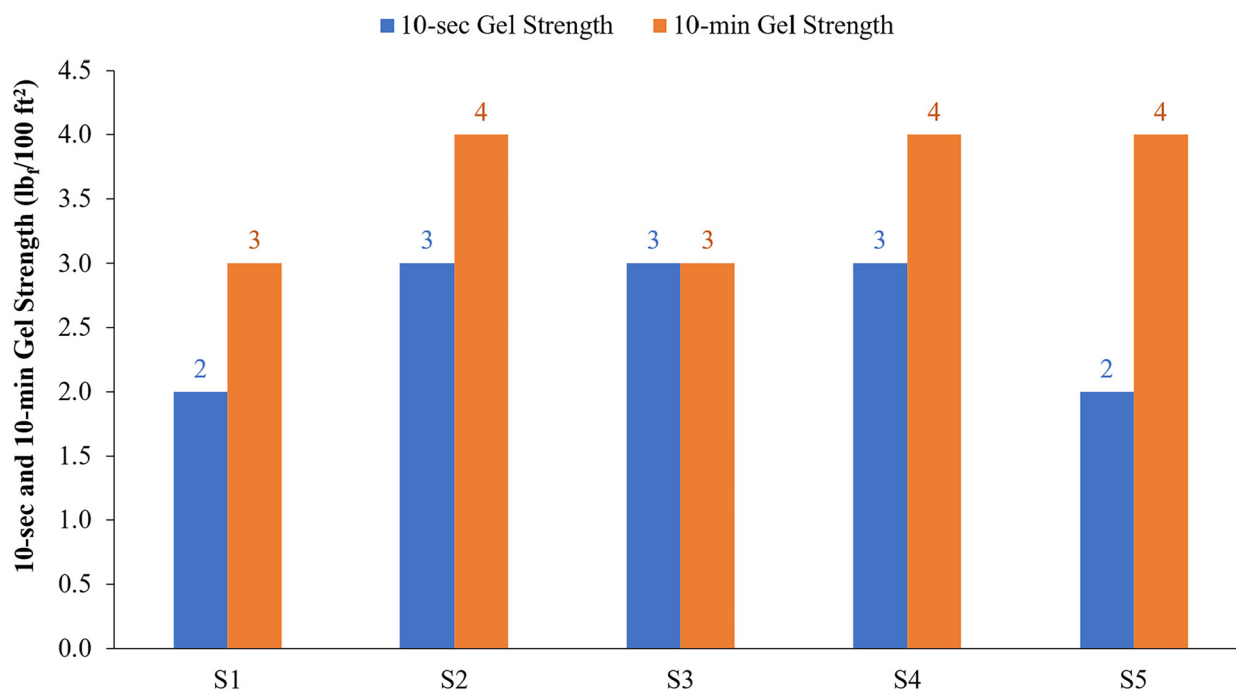


Figure 10. Gel strengths at 10 s and 10 min for all samples

Table 7. Corrosion performance assessment

Sample	Initial Weight (g)	Final Weight (g)	Weight Loss (g)	Weight Loss (%)	Corrosion Rate	Acceptability
S1	40.500	40.455	0.045	0.11	Very Low	Excellent
S2	40.800	40.662	0.138	0.34	Low	Good
S3	41.380	41.338	0.042	0.10	Very Low	Excellent
S4	41.096	41.015	0.081	0.20	Very Low	Excellent
S5	38.737	38.735	0.002	0.01	Minimal	Outstanding

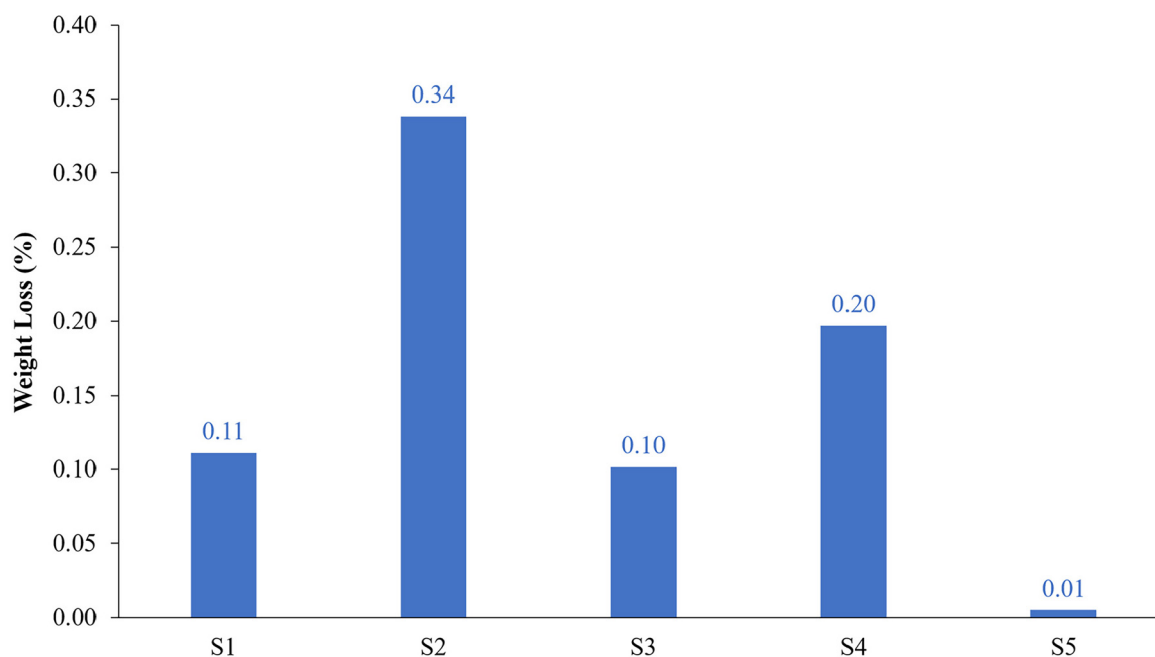


Figure 11. Corrosion test results showing the weight loss per sample

thermal stability, and high-pressure/high-temperature (HPHT) conditions were not investigated. Therefore, further studies are recommended before field application.

4. CONCLUSIONS

This comprehensive laboratory investigation demonstrated the viability of red mud as a calcite alternative in water-based drilling fluids for drilling across reservoir sections. The key findings of this study are as follows:

- The sample with full replacement of calcite by red mud achieved a comparable apparent viscosity of 25.0 cP while that for calcite was 27.5 cP.
- Mixed formulations optimized cutting transport efficiency with ideal yield point/plastic viscosity ratios (1.00–1.08).
- The gel strength and corrosion resistance were acceptable across all tested concentrations.
- Samples S3 and S4 (50–75% red mud contents) provided an optimal balance of rheological properties.
- Pure red mud systems showed promise for specialized applications requiring a high plastic viscosity.
- Mixed systems offer flexibility for various drilling conditions and requirements.

This study established a foundation for sustainable drilling fluid development while addressing critical waste management challenges. Further investigation into the high-temperature performance and field validation will advance commercial implementation prospects.

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